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Study on Steel Reinforced Concrete Composite Beams Strengthened with Steel Plates or CFRP Sheets

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ABSTRACT: To study the mechanical behavior of steel reinforced concrete composite beams strengthened with externally bonded steel plates or CFRP sheets, 7 beam specimens, in which there are no longitudinal steel bars, are tested. Test and theoretical analysis results show that the strengthening method using steel plates for composite beams is more effective than the method using CFRP sheets. With the help of additional measures, for example, the *U* type stirrups glued at the side of longitudinal steel plates, the strengthened beam may have a good deforming ability. The research results have been used and verified in the strengthening project for a historical high-rise building in Shanghai.

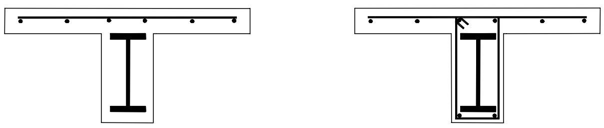
1 INTRODUCTION

From the beginning of last century, many distinguished buildings were built along the Huangpu River in Shanghai, the Bund in this orient metropolitan (Figs. 1 and 2). Because of different kinds of architectural styles, most of the buildings in Bund zone are protected by the government of China. The most common structural system used in buildings located in Bund is the system of steel beam and steel column covered by concrete for the purpose of fireproof. There are no longitudinal steel bars inside the concrete cover. And, this kind of the steel-concrete composite structural member is different from modern composite members in which there are longitudinal steel bars and hoops between steel member and concrete cover (Fig. 3). During service life of a century, mechanical behavior of this kind of composite members in most of buildings has deteriorated. It is very important to strengthen deteriorated structural members for the purpose of protection for historical buildings.

Figure 1 : Buildings located in Bund of Shanghai

Figure 2 : Bank of China

Among different kinds of strengthening methods for concrete structural members, it is very convenient to strengthen the member by gluing steel plates or CFRP (carbon fiber reinforced polymer) sheets on its surface (ACI Committee 440 2000, CECS 146:2003, Hollaway,et al. 2002). But there is limited experience about the strengthening of steel reinforced concrete (SRC) composite structural members using steel plates or CFRP sheets (Photiou, et al. 2006, Mckenna and Erki 1994).To study the mechanical behavior of steel reinforced concrete composite beams strengthened with steel plates or CFRP sheets, 7 beam specimens are tested and analyzed in this paper. The study results are used in the strengthening project of the building of Bank of China which was built in 1937, a historical high-rise building located in Bund of Shanghai (Fig. 2).



(a) beam in historical buildings (b) beam in modern buildings

Figue 3 : sections of steel reinforced composite beams

2 TEST OF BEAMS

2.1 Specimens

To simulated the real beams used in historical buildings shown in Fig. 1 and Fig. 2, 7 steel reinforced concrete composite T-beam specimens, *L*1~*L*7, were designed and constructed. The *I* shape steel structural member is covered by concrete and there are no longitudinal steel bars in every beam. Among 7 beam specimens, *L*1 and *L*6 are not strengthened, which can serve as the references in the analysis of test results. *L*2, *L*3 and *L*7 are strengthened by gluing longitudinal steel plates on the bottom surface of the beam and 3 steel *U* type stirrups at each side of the beam to guarantee the anchorage of the longitudinal steel plate (Jones and Swamy 1988). The *U* type stirrups are anchored by bolts. *L*4 and *L*5 are strengthened by gluing longitudinal CFRP sheets and CFRP *U* type stirrups. The details of the T-beam specimens are listed in Fig. 4.

2.2 Test set-up

All of beams were tested in four points bending static loading (Fig. 5). Two equal vertical loads *P* were applied on the top of the test beam through a loading jack and a steel distribution beam. First the load was increased step by step. The increment of the load is ΔP=10kN. When the longitudinal steel structural member inside the beam yielded the experiment was switched to the displacement control. The test was terminated when the beam lost its flexural bearing capacity. All of the data for the value of the load, the value of the displacement, and the value of the strain were acquired through the data acquisition system. Cracks were observed and recorded on the surface of the beam.

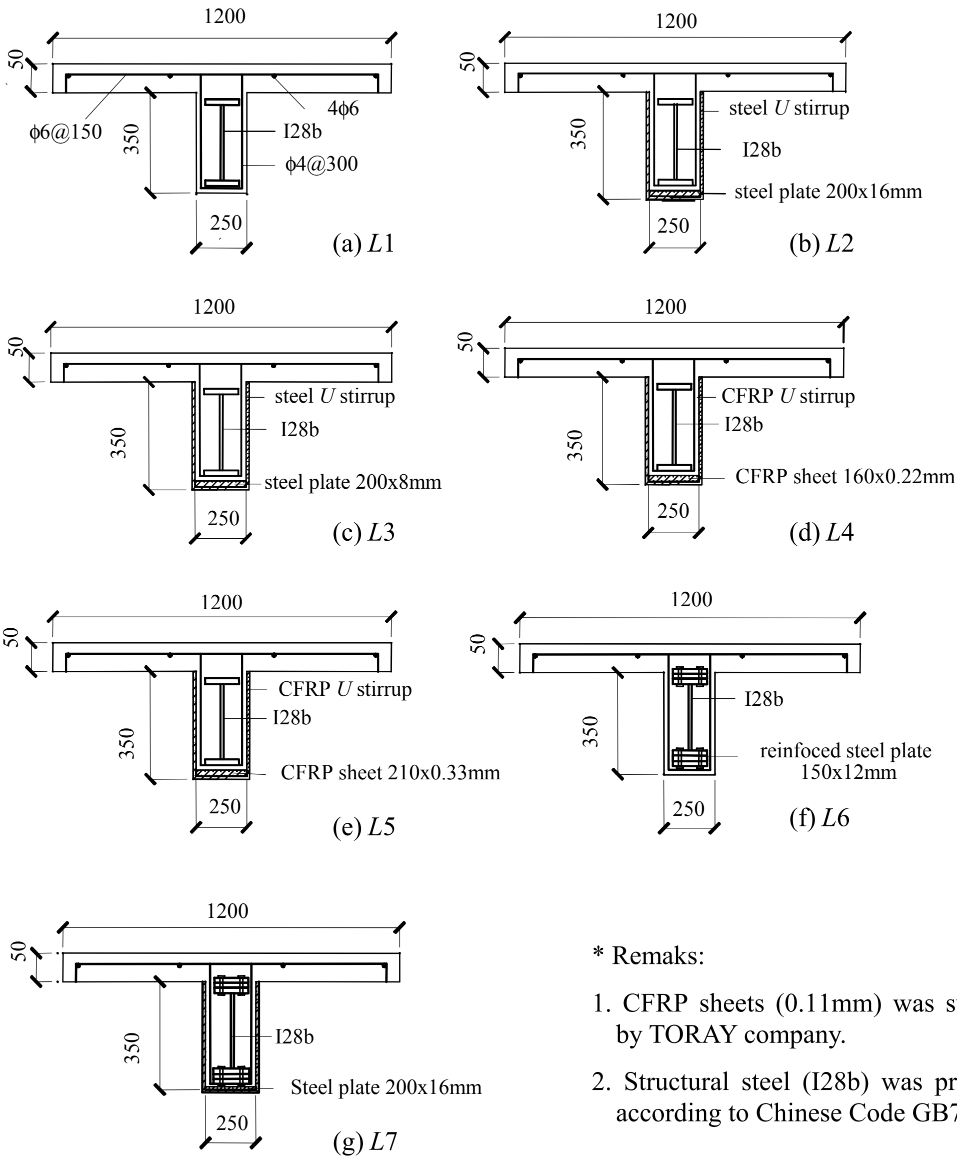
3 RESULTS OF TEST

3.1 Mechanical properties of materials

Compressive tests for concrete material show that the average cubic compressive strength of concrete for *L*1~*L*4 is 16.4 MPa and for *L*5~*L*7 is 23.5MPa, and the average prism compressive strengths of concrete are 15.3 and 19.7MPa respectively. The tensile yielding strength for steel *I* beam is 259.5MPa, for 6 mm and 8 mm steel plate is 287.1MPa and 267.7MPa respectively. The strengths of concrete and steel are close to that of the original materials in the real building. Tensile tests for CFRP sheets show that the average tensile strength of CFRP is 4286MPa and the elastic modulus is 256520MPa.

3.2 Failure modes of beams

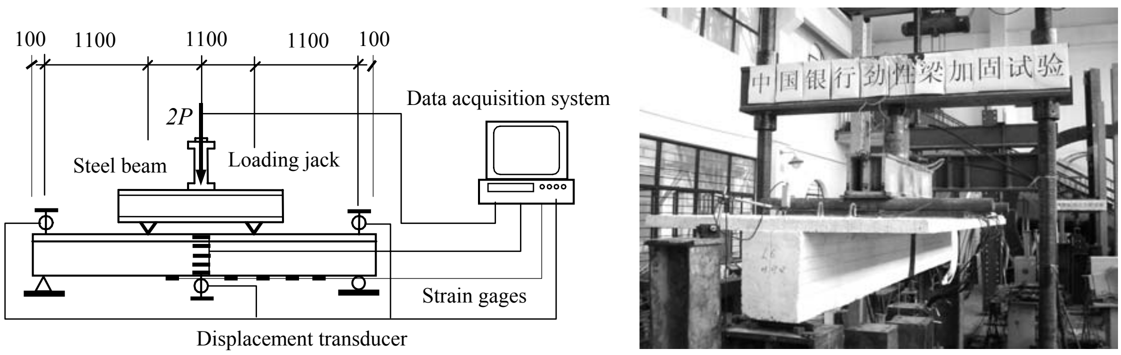
Typical bending failure mode was observed in the tests of reference Beam *L*1 and *L*6. With the increase of the load, concrete cracked, longitudinal steel structural member yielded. Being lack of shear transfer connectors and hoops, *I* shape slipping crack appeared at the interface between the steel structural member and the concrete. Finally, divisive crack between flange and web arose and the beam lost its bearing capacity (Fig. 6a and Fig. 6f).



* Remaks:

1. CFRP sheets (0.11mm) was supplied by TORAY company.
2. Structural steel (I28b) was produced according to Chinese Code GB706-88.

Figure 4 : Detailed section view of testing beams



(a) Data acquisition system (b) Loading system

Figure 5 : Test set-up

With the help of steel stirrups at both sides of longitudinal steel plates, the mechanical behavior of strengthened beams (beam *L*2, beam *L*3 and beam *L*7) is greatly improved. Cracking loads of beams are higher than that of un-strengthened beams. After yielding of both longitudinal steel structural member inside the beam and steel plate outside the beam, the slipping cracks were observed at the shear span of the beam (Fig. 6c), then concrete along the interface between web and flange crushed, and the beam damaged. Without the help of the shear transfer connectors and hoops, the contribution of the flange in compressive zone to the bearing capacity of the beam is limited. Because more steel plates were used, beam *L*2 and beam *L*7 broke shortly after major shear crack appeared at last (Fig.6b and Fig. 6g).

With the help of 3 CFRP stirrups at both sides of longitudinal CFRP sheets, CFRP sheets can work well together with the strengthened SRC composite beam at the beginning of the loading (beam *L*4 and beam *L*5). With the increase of the load, the strain of CFRP sheets and the strain of longitudinal steel structural member increased in same way. Cracking loads for CFRP strengthened beams are almost same with that for un-strengthened beams. The maximum width of the crack and the space between adjacent cracks on the strengthened beam are smaller than that of the un-strengthened beam. Because small amount of CFRP sheet was applied on beam *L*4, the CFRP sheet broke shortly after the steel structural member yeilded, the CFRP stirrup nearby broke at the same time (Fig. 6d). In spite of the amount of CFRP sheets was increased, failure of beam *L*5 was initiated by the yielding of the steel structural member. Under virtually constant bending, the concrete in compressive zone of beam *L*5 did not crush till *U* type stirrups and concrete cover peeled off at one side of the beam (Fig. 6e).

3.3 Load-deflection curves

Load-deflection curves for all of the testing beams are shown in Fig. 7. Characteristic points, such as yielding point of steel structural member and ultimate deflection, can be seen in the Table 1.

Table 1 : Bearing capacity and deflections

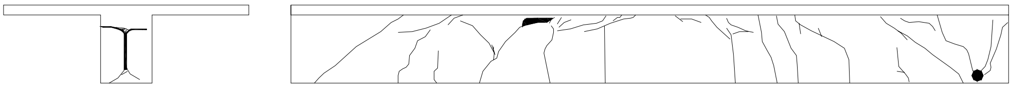
No.of beam	Cracking load P_{cr}	Yielding load P_y	Yielding deflection Δ_y	Bearing capacity P_u	Ultimate deflection Δ_u	Calculated bearing capacity P_c
	kN	kN	mm	kN	mm	kN
L1	20	144	5.20	248	87.8	242
L2	70	323	10.34	359	150.0	(439)
L3	40	250	5.50	349	21.6	367
L4	20	226	30.18	228	49.6	256
L5	20	254	19.29	273	26.4	278
L6	20	317	8.32	347	34.4	370
L7	30	400	9.19	400	16.5	(640)

* (shear failure beam)

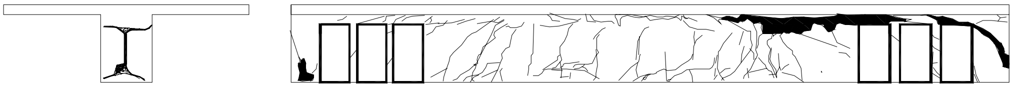
3.4 Strain distribution in the section of the beam

The strains of the steel *I* beams, steel plates and CFRP sheets in the section at the middle span of testing beams are shown in Fig.8. All steel structural members are yielded in the test. Strains in CFRP sheets are larger than that in steel plates. Under ultimate load, strains measured in CFRP sheets and steel plates of a testing beam are about 6000με and 3000με respectively.

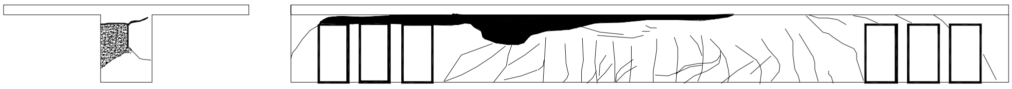
The strain distribution along the section of two concrete beams is shown in Fig. 9. Before cracking, the linear distribution of the strain along the height of the beam can be observed. Even though the steel *I* beam have yielded, the approximate linear distribution of the strain can still be observed in the test. The plane section assumption can be used in calculation of bending bearing capacity of steel reinforced concrete composite beam strengthened with steel plates or CFRP sheets.



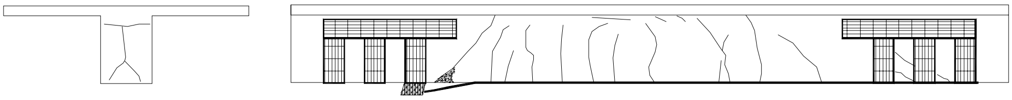
(a) *L*1: structural steel yeilded and concrete crushed



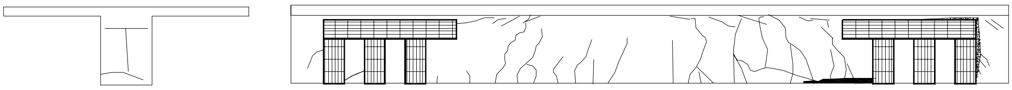
(b) *L*2: shear failure



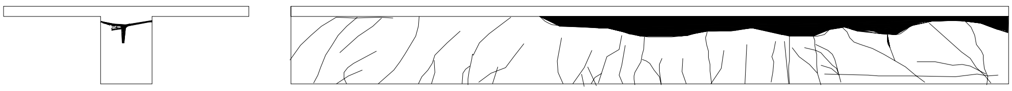
(c) *L*3: steel plate and structural steel yeilded



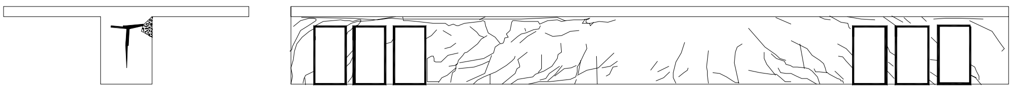
(d) *L*4: structural steel yeilded and CFRP sheet broke



(e) *L*5: structural steel yeilded and concrete peeled off



(f) *L*6: structural steel yeilded and concrete crushed



(g) *L*7: shear failure

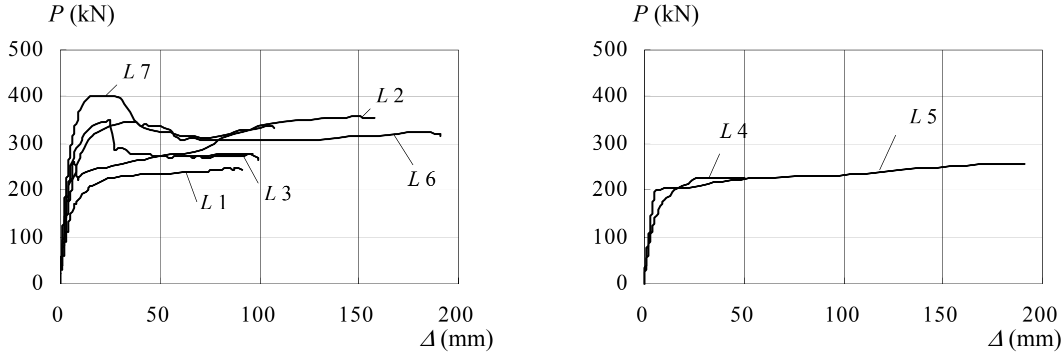
(h) *U* stirrup rotated (i) CFRP sheet broke

Figure 6 : Failure modes of testing beams

4 ANALYSIS OF TEST RESULTS

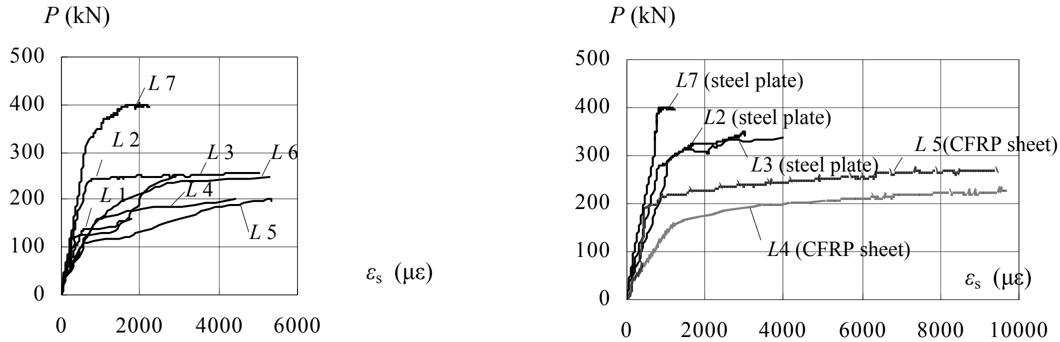
4.1 Bearing capacity of strengthened beam

Values of bearing capacity for all of testing beams are listed in Table 1. Comparing with beam *L*1, it can be seen that the bending bearing capacity of SRC composite beams can be increased more than 40% by gluing steel plate externally. The bending bearing capacity of the beam *L*5 strengthened by 3 lays of CFRP sheets is increased about 10%.With the help of 2 layer of reinfoced steel plates fasted on the steel structural member by bolts, bearing capacity of beam *L*6 was increased 40% than that of *L*1, and the value of beam *L*7 strengthened by steel plate was increased 15% than that of *L*6. Test results show that the strengthening method using steel plates for composite beams is more effective than the method using CFRP sheets.



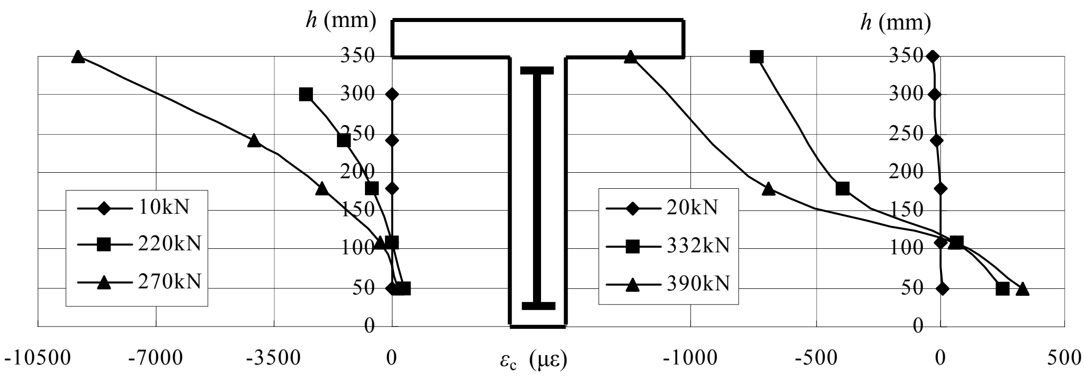
(a) Beam *L*1~*L*3 and *L*6~*L*7 (b) Beam *L*4 and *L*5

Figure 7 : Load-deflection curves of testing beams



(a) for structural steel beam (b) for steel plate or CFRP sheet

Figure 8 : Load-strain curves of testing beams



(a) Beam *L*5 (b) Beam *L*7

Figure 9 : Load-strain distribution of concrete beams

4.2 Deforming ability of strengthened beams

Deflection values corresponding to loads applied on beams when steel structural member or steel plate yields and ultimate deflection values are listed in Table 1. The strengthened beam with *U* type stirrups has a large deformation to warn the damage after yielding of the steel. With the help of the U type stirrups glued at the side of longitudinal steel plates, the strengthened beams may have a good deforming ability, the ratio of maximal deflection to clear span for steel plates strengthened beam is more than 1/50 at least.

5 CALCULATION OF THE BEARING CAPACITY OF STRENGTHENED BEAMS

Based on failure modes of beams, the bearing capacity of the strengthened beam can be calculated according to the specification of Chinese Code (JGJ138-2001) (Fig. 10):

when $x \le h_f$,

$$M_u = f_c w x (h_0 - \frac{x}{2}) + f_a^{'} A_a^{'} (h_0 - a_a^{'}) + \left[\frac{1}{2}(\delta_1^2 + \delta_2^2) - (\delta_1 + \delta_2) + 2.5\frac{x}{h_0} - (1.25\times\frac{x}{h_0})^2 \right] t_w h_o^2 f_a \tag{1}$$

and

$$x = \frac{fA + (\delta_1 + \delta_2) t_w h_0 f_a}{f_c w + 2.5 t_w f_a} \tag{2}$$

For beam strengthened by steel plate, $fA = f_y A_s$ (3)

For CFRP sheet strengthened beam, $fA = E_f \varepsilon_{f,e} A_f$ (4)

when $x > h_f$,

$$M_u = f_c (w-b) h_f (h_0 - \frac{h_f}{2}) + f_c b x (h_0 - \frac{x}{2}) + f_a^{'} A_a^{'} (h_0 - a_a^{'}) + \left[\frac{1}{2}(\delta_1^2 + \delta_2^2) - (\delta_1 + \delta_2) + 2.5\frac{x}{h_0} - (1.25\times\frac{x}{h_0})^2 \right] t_w h_o^2 f_a \tag{5}$$

and

$$x = \frac{fA + (\delta_1 + \delta_2) t_w h_0 f_a - f_c (w-b) h_f}{f_c b + 2.5 t_w f_a} \tag{6}$$

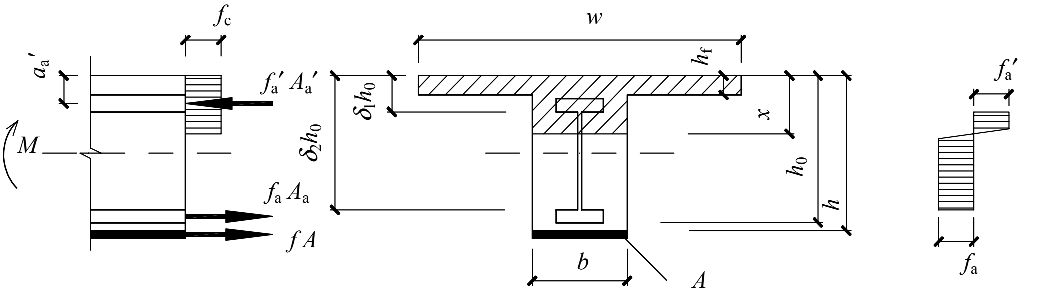


Figure 10 : Model of calculation

where f_c =prism compressive strength of concrete, w = the width of flange, f_a'= compressive yielding strength of steel structural member, A_a'= area of flange plate, h_0 = the effective height from the resultant force point of flange and plate or sheet to top of beam, f_a= tensile yielding strength of steel structural member, t_w= the width of web of I beam, δ_1 and δ_2= parmeters shown in Fig. 10, x = the height of compressive zone, f_y= tensile yielding strength of steel plate, E_f= the elastic modulus of CFRP, $\varepsilon_{f,e}$= 0.006, the effective tensile strain of CFRP sheet, A_f= area of CFRP sheet, h_f= the height of the flange, b = the width of the beam.

The calculation results of bearing capacity for testing beams are listed in Tab.1. Comparing with the testing results, it can be seen that the theoretical method can be used to calculate the flexural capacity of the beam strengthened by steel plates or CFRP sheets. Considering the slipping effect, the final value of flexural bearing capacity of a strengthened beam can be got safely by multiplying a reduction factor, 0.9, to the calculation result with Eq. (1) or Eq. (5).

6 APPLICATON OF RESULTS

Based on the test and the theoretical results, some steel reinforced concrete composite beams in the building of Bank of China have been strengthened using steel plates (Fig. 11). The budget shows that the expense of the strengthened method using steel plates is less than that of the method using CFRP sheets.

Figure 11 : Strengthened beams in Bank of China

7 CONCLUSIONS

It is possible to strengthen the steel reinforced concrete composite beams without any longitudinal steel bars and hoops by gluing the steel plates or CFRP sheets externally. The longitudinal steel plate or CFRP sheet bonded on the bottom of the beam can work well together with the concrete, the bearing capacity of the beam can be increased significantly with proper amount of steel plate or CFRP sheet. Meanwhile, the strengthened beam has a good deforming ability to warn the damage of the beam under ultimate load after yielding of the steel. Test and theoretical analysis results show that the strengthening method using steel plates for composite beams is more effective than the method using CFRP sheets. The research results have been used and verified in a strengthening project for a historical high-rise building in Shanghai. The extensive test study and theoretical analysis on mechanical behavior of SRC composite beams strengthened with steel plates or CFRP sheets will be done in the future.

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